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MEMORANDUM REPORT ARCCB-MR-87036

LAUNCHABILITY OF BASE-DRIVEN ELECTROMAGNETIC PROJECTILES

C. G. HOMAN

P. M. VOTTIS

DECEMBER 1987

US ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
CLOSE COMBAT ARMAMENTS CENTER
BENÉT WEAPONS LABORATORY
WATERVLIET, N.Y. 12189-4050

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The launchability of penetrator projectiles at the velocities attainable in electromagnetic (EM) launch is examined. By assuming a base-driven model, theoretical expressions are derived for the ratio of projectile mass to the mass of the penetrator core (M_T/M_P) as a function of the ratio (λ) of the length of the penetrator (ℓ) to the unsupported length of the penetrator (ℓ_0). This analysis relates the specific strengths and densities of the penetrator and sabot materials to λ and M_T/M_P.

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20. ABSTRACT (CONT'D)

It is shown that an electromagnetic projectile made from materials used in fielded penetrators and launched with a maximum acceleration of 150,000 G's can have an unsupported length (ℓ_0) of 5 to 7.2 cm dependent on the material yield criteria used. Using conservative design criteria similar to those used in the XM829 round, we show that a projectile of 2 kg mass having a 1 kg penetrator core may be launched in the base-driven mode without exceeding material properties.

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INTRODUCTION

Electromagnetic (EM) railguns use either a plasma armature or a solid metallic armature. The plasma exists at the base of the projectile and provides a base pressure type of drive. A simple solid armature permits the current to cross at its rear face. Thus, in an unaugmented railgun, $\bar{J} \times \bar{B}$ body forces can produce a base-driven mode, similar to standard propellant-driven guns.

The use of augmenting magnetic fields provides a field in forward parts of the armature. Use of axially graded resistivity can distribute current throughout the armature. The combined effect is to distribute $\bar{J} \times \bar{B}$ forces throughout the armature structure, which can substantially reduce launch stresses. The net effect is to permit larger projectile masses and accelerations than can be accommodated in the base-driven mode.

Projectile base-drive must then be treated as the baseline or minimally acceptable mode of launch. More generally, base-drive can be thought of as plane-drive where the projectile is driven at a single plane. Regions forward of the plane experience compressive stresses and regions rearward experience tensile stresses. In this report, we provide an analysis of the base-driven mode, and describe advantages inherent in body force loading of EM launched projectiles. It should be noted that results for base-driven projectiles also apply to double length, double mass, center plane-driven projectiles whose rear tensile region is a mirror image of the forward compressive region.

Usually, a penetrator is a long rod. For a given acceleration, there is a maximum rod length ℓ_0, that can be base-driven without achieving compressive failure at the rod base. Adding length to the base requires that additional support material be provided to prevent compressive failure. The simplest treatment is to provide surrounding material that drives the added central rod by shear at its cylindrical surface, and is itself driven by axial compressive force at its annular base area beyond the rod radius (see Figure 1). The compressive force is such as to cause incipient compressive failure in the support material. This provides a least mass solution. The added mass can be a monolithic continuation of the rod material or can be lightweight high strength sabot material.

The following solution treats rod and support material as separate types, with the monolith being the trivial case of equal properties. The objective of the solution is to determine the ratio of parasitic support mass to penetrator mass, or, as commonly displayed, the ratio of total in-bore mass to penetrator mass.

This memorandum report describes a preliminary study of the question of launching weapon grade projectiles at the higher velocities attainable with EM railguns. As a design condition, we will assume that a projectile, having 16 MJ of muzzle energy, was launched with a maximum acceleration of 150,000 G's.

We will approach this study by first looking at the worst case condition of a base-driven penetrator whose sabot is made of the same material as the penetrator. Next, we will consider modern penetrator technology where the sabot is constructed from lightweight aluminum alloy with high specific strength and is designed to more appropriately distribute launch stresses. Examples of such rounds include the XM833 and XM774 penetrator rounds for the 105-mm cannon. We will also consider the case in which the sabot is an integral part of the penetrator by relaxing the normal rod-like shape of the penetrator without considering the efficacy of penetration by such projectiles.

Finally, we will examine the differences in launch behavior of an EM round which, in the case of a solid armature drive, is <u>not</u> base-driven. The driving force or stress in an EM projectile is proportional to the current distribution through the sabot/penetrator, and proper distribution can significantly reduce launch failure of penetrators.

This report is not intended to answer the question of weaponizability of EM launchers for a specific application. That is a larger question involving not only the launchability of projectiles, but the penetrability of such projectiles and the considerations of size and mass of the launcher system.

THEORETICAL ANALYSIS

Base-Driven Projectiles

Consider the idealized penetrator/sabot configuration shown in Figure 2. The unsupported penetrator length, ℓ_o, has a mass $m(\ell_o)$ equal to

$$m(\ell_o) = \rho A_o \ell_o \tag{1}$$

where ρ is the density of the penetrator material. For a base-driven penetrator, the failure stress, σ_y, of the penetrator material limits the maximum acceleration, a_{max}, that the material can tolerate without failure, i.e.,

$$A_o \sigma_y = m(\ell_o) a_{max} = \rho A_o \ell_o a_{max} \tag{2}$$

In order to increase the penetrator length beyond ℓ_o, we must support each additional segment which increases the force appropriately. Note that at the maximum acceleration, the increased force supports only the increased mass due to the sabot and penetrator length. If the sabot material properties are density ρ' and yield strength σ_y', then the additional mass is

$$dm \doteq \pi \rho' r^2 d\ell + \pi(\rho - \rho') r_o^2 d\ell \tag{3}$$

and the incremental force required to accelerate this mass is obtained from the condition that the additional mass must have the same acceleration as the core, i.e.,

$$\sigma_y{}'A = M_T a_{max} \tag{4}$$

which immediately determines the value of r'

$$r' = (\sigma_y/\sigma_y{}')r_o \tag{5}$$

Using Eqs. (2) through (5), we can show

$$\int_{\ell_o}^{\ell} d\ell = \frac{2\ell_o\sigma_y{}'}{S} \int_{r'}^{r} \frac{r\,dr}{r^2\rho' + \Delta\rho r_o{}^2} \tag{6}$$

obtaining finally

$$r^2 = (\frac{\sigma_y}{\sigma_y{}'} + \frac{\Delta\rho}{\rho})r_o{}^2 \exp[b(\lambda-1)] - \frac{\Delta\rho}{\rho'} r_o{}^2 \tag{7}$$

where

$$\Delta\rho = \rho - \rho' \ ; \quad S \equiv \frac{\sigma_y}{\rho} \ ; \quad b = \frac{S}{S'} \ ; \quad \lambda = \frac{\ell}{\ell_o}$$

We may now calculate the mass increase using Eqs. (3) and (7) obtaining

$$\int_{m(\ell_o)}^{m(\ell)} dm = \pi r_o{}^2 \int_{\ell_o}^{\ell} \{[(\frac{\sigma_y}{\sigma_y{}'} + \frac{\Delta\rho}{\rho'})\exp[b(\lambda-1)] - \frac{\Delta\rho}{\rho'}]\rho' + \Delta\rho\}d\ell$$

and finally obtain the ratio of the total mass M_T to penetrator mass M_P of

$$\frac{M_T}{M_P} = (b + \frac{\Delta\rho}{\rho})[\frac{e^{b(\lambda-1)} + b-1}{b\lambda}] \tag{8}$$

For the case where the sabot and penetrator are of the same material,

$$\frac{M_T}{M_P} = \frac{e^{\lambda-1}}{\lambda} \tag{9}$$

Figure 3 is a plot of the growth factor M_T/M_P for actual penetrator and sabot materials. Curve A represents the worst case solution for a projectile having the sabot made from penetrator material (Eq. (9)). Curve B is obtained using the specific strength of either depleted uranium or tungsten alloy penetrators and aluminum alloy sabot materials as calculated from actual stress-to-failure data for tensile tests (ref 1). Curve C is obtained by increasing those stresses by 50 percent to allow for the additional failure strengths in compression. Curve D represents the case of sabotless penetrators as described for the idealized EM launch below. Such a projectile can also result from defining the total mass as penetrator in Eq. (9) and whose radius is determined from Eq. (7). Figure 4 shows such a projectile.

Ideal EM Launch

It must be realized that since the Lorentz force, $\bar{F} = \bar{J} \times \bar{B}$, is the driving force for EM launch, by properly designing the sabot/armature, a greatly improved distribution of launch stresses can be made along the total length of the projectile. Of course, the penetrator could act as its own armature; however, this is not always a practical solution with respect to other EM launch criteria such as sabot/armature resistance and the desirability of injecting the launch package into the railgun at some finite velocity. The final configuration of an EM launch projectile will probably have an armature/sabot which will provide a desirable current path as well as provide some initial base drive from an expansion gas. This configuration is being considered in Benet Laboratories EM Hybrid Expansion Railgun demonstrator program. Thus, the curve representing a real weaponized EM penetrator projectile will lie somewhere between curves B and D.

[1] M. A. Scavullo, J. H. Underwood, and J. J. Zalinka, "An Acceptance Test Method for Materials Used in Kinetic Energy Projectiles," ARDEC Technical Report ARCCB-TR-86031, Benet Weapons Laboratory, Watervliet, NY, September 1986.

Shear Force Considerations

What is the maximum shear stress developed in supporting the additional penetrator length $\ell - \ell_o$? The force F_A that must be provided is

$$F_A = [M_P - M_P(\ell_o)]a_{max}$$

$$= \pi \rho r_o^2 (\ell - \ell_o) \frac{\sigma_y}{\rho \ell_o} = \pi r_o^2 \sigma_y (\lambda - 1) \tag{10}$$

Thus, the average shear stress is

$$\tau = \frac{F_A}{A_{shear}} = \frac{\pi r_o^2 \sigma_y (\lambda - 1)}{2\pi r_o (\ell - \ell_o)} = \frac{r_o \sigma_y}{2\ell_o} \tag{11}$$

which must be supported by the material (either sabot or penetrator) having the lowest shear strength.

Specific Example of Base-Driven Penetrator/Sabot

Assume a mass ratio $M_T/M_P = 2$. From Figure 3 we can take the conservative value $\lambda = 6$. The unsupported length ℓ_o is calculated from Eq. (2) assuming a maximum acceleration of 1.5×10^5 G's as

$$\ell_o = \frac{\sigma_y}{\rho a_{max}} \approx 5 \text{ cm}$$

where $\sigma_y = 200$ Ksi tensile yield strength and $\rho = 19 \text{ g/cm}^3$. Thus, the total length, ℓ, of the projectile to the end of the support is 30 cm. From reported penetration data (ref 2), we can assume $\ell/D = 20$, then $D = 1.5$ cm. The penetrator mass is

$$M_P = \frac{\rho \pi D^2 \ell}{4} \approx 1 \text{ kg}$$

and

[2] G. E. Hauver and A. Melani, "Penetration by Very Long Rods," BRL Technical Report BRL-TR-2666, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, August 1985.

$$M_T \approx 2 \text{ kg}$$

The average shear stress at the sabot/penetrator interface is calculated from Eq. (11) and is

$$\tau_{AV} = 15{,}000 \text{ psi}$$

which is comparable to current practice. The sabot radius at the projectile rear is given by Eq. (7), and for the above case is 28.5 mm.

This projectile is thus a 57 mm diameter round weighing 2 kg with a 15 mm diameter penetrator of 30 cm length. The muzzle velocity for 16 MJ launch energy is 4 km/sec.

CONCLUSIONS

The shapes and masses of base-driven saboted projectiles with rod-like penetrators have been determined. The case of sabot properties equal to penetrator properties produces a projectile that is unacceptably heavy for useful large caliber rod lengths. However, treated as a monolith, wherein the sabot and penetrator are integral and both comprise the flight projectile, a reasonably slender exponential cone-like form results.

For penetrators driven by aluminum sabots with an M_T/M_P ratio of approximately two, λ approaches 7 using a compressive yield strength 1.5 times the tensile yield strength. Assuming $M_T/M_P = 2$ as a useful upper limit means that tungsten penetrators are limited to about $7\ \ell_o = 50$ cm and uranium penetrators to about 40 cm for the case of aluminum sabot pure base-drive. Shear strengths required for the coupling from sabot to penetrator appear adequate for these projectiles at L/D's of interest at 150,000 G's.

Launching of longer penetrators by aluminum sabots would require staging, i.e., multiple drive zones along the penetrator with each zone shorter than the $7\ \ell_o$ length above to keep $M_T/M_P \leqslant 2$. It should be noted that each stage can also accommodate an additional unsupported length of penetrator ℓ_o, trailing the sabot supported zone. This length represents the maximum length that can be pulled without tensile failure at its forward plane. It is equal in length to the ℓ_o discussed in the text if penetrator compressive and tensile strengths are equal.

With introduction of the concept of staging, we begin to move away from the condition of pure base-drive into the realm of penetrator distributed-drive. An area that needs investigation and promises great benefits is the development of $\bar{J} \times \bar{B}$ body forces within the penetrator. These may provide only a part of the acceleration force to ease the sabot loading. In the ultimate design case, a sabotless penetrator would find each portion of its volume accelerated by a uniform $\bar{J} \times \bar{B}$ body force, and no significant internal stress would be created. This would most likely represent a design inefficiency, and some compromise between internal stresses and the applied body force distribution would more equally work all the material capabilities. This type of system can be met with a sabot of graded resistivity and augmented magnetic fields which provide flux at the front of the projectile.

Finally, we conclude that, using current technology, a penetrator/sabot can be readily designed to withstand the stresses generated by launching a 2 kg penetrator/sabot projectile with peak acceleration of 1.5×10^6 m/sec^2 with a rail launcher. Thus, the weaponization of EM launchers of this magnitude will be determined by consideration of utility at the target (penetrability of target, etc.) and the railgun system's efficiency (size, weight, mobility, etc.), not by launchability. The program at Benet Laboratories is focused on the latter considerations through the Hybrid Expansion Railgun and Superconducting Augmented Railgun studies.

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1. M. A. Scavullo, J. H. Underwood, and J. J. Zalinka, "An Acceptance Test Method for Materials Used in Kinetic Energy Projectiles," ARDEC Technical Report ARCCB-TR-86031, Benet Weapons Laboratory, Watervliet, NY, September 1986.

2. G. E. Hauver and A. Malani, "Penetration by Very Long Rods," BRL Technical Report BRL-TR-2666, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, August 1985.

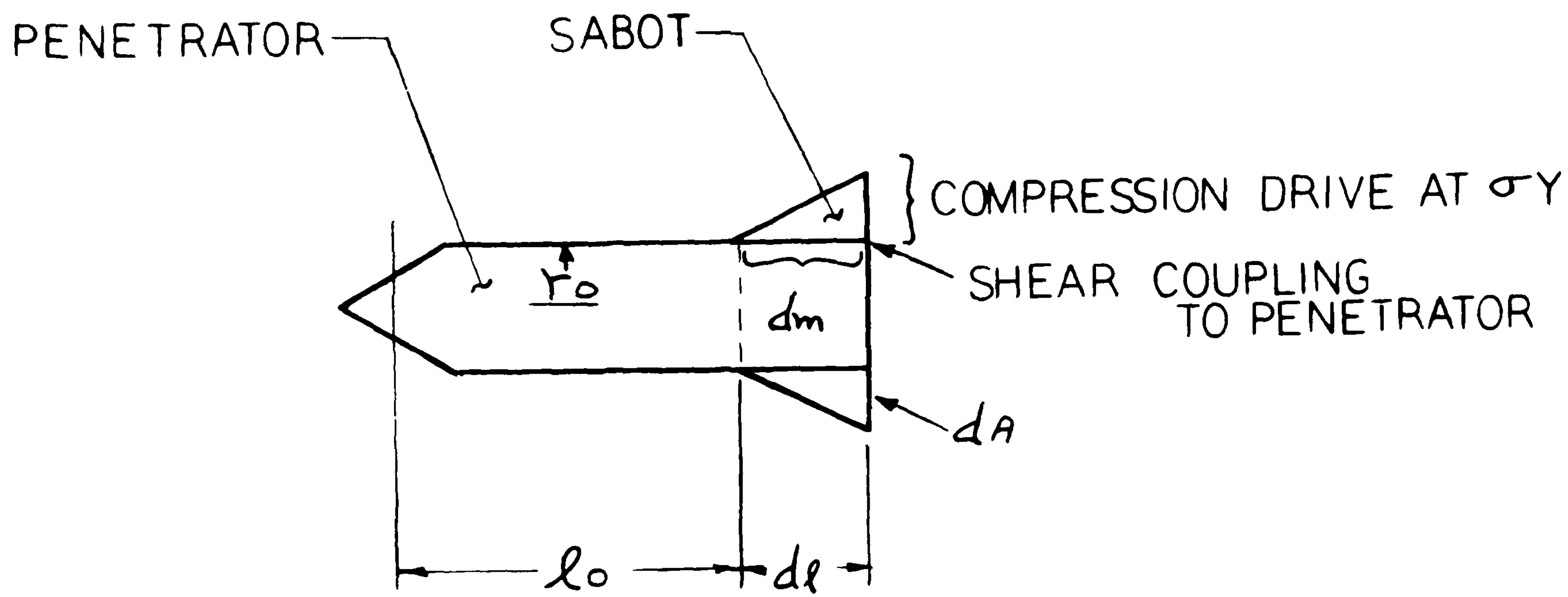

FIGURE 1. ROD SUPPORT METHOD

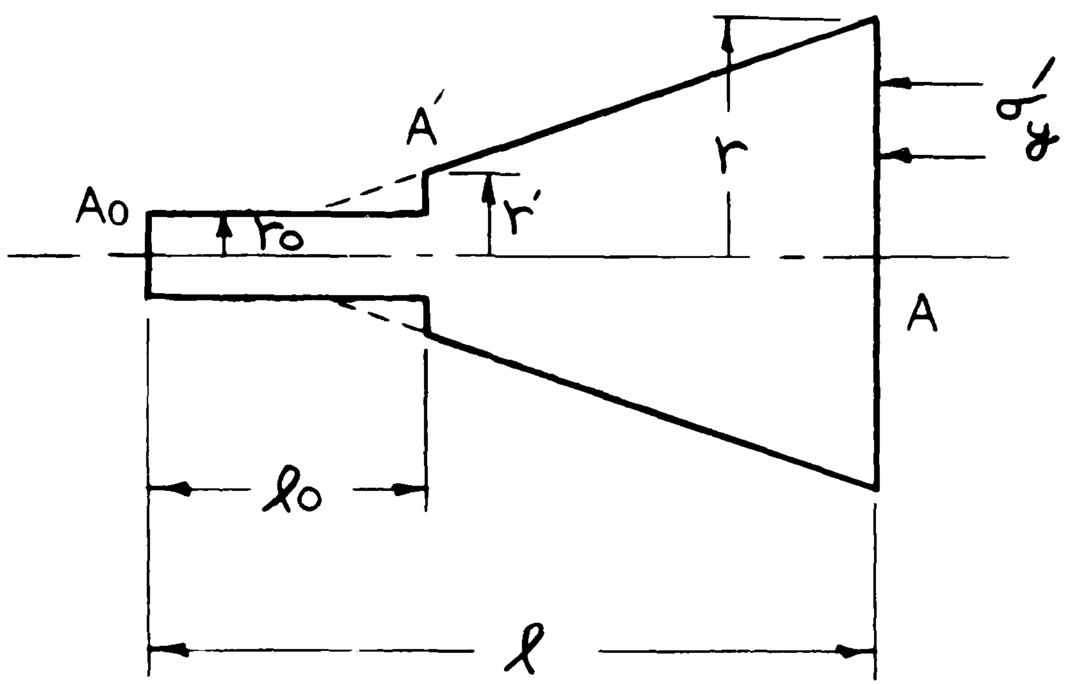

FIGURE 2. IDEALIZED PENETRATOR/SABOT CONFIGURATION FOR ANALYSIS

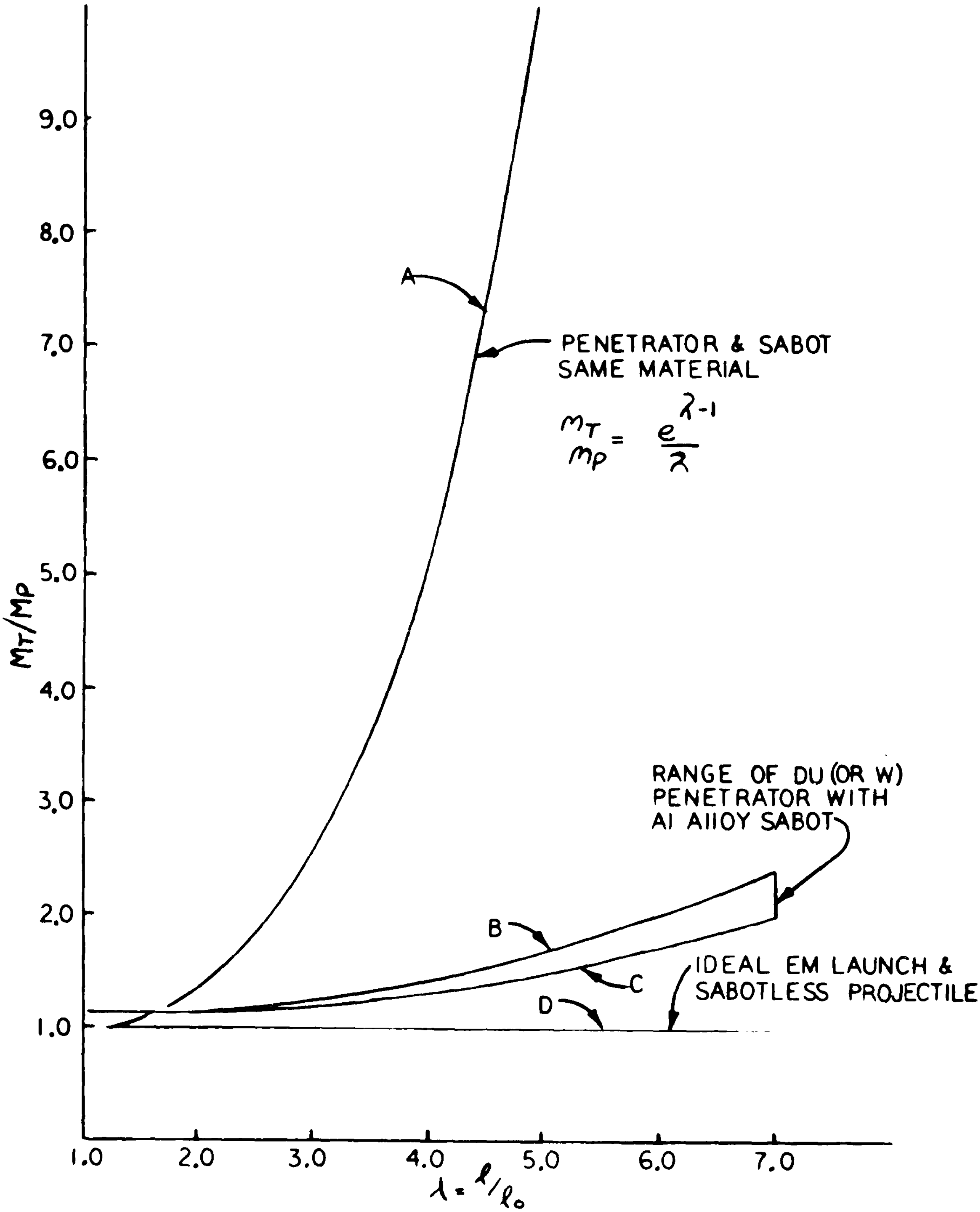

FIGURE 3. MASS GROWTH FACTOR M_t/M_p VS. λ

GENERAL $L/D = 5.5$

$$r(\ell) = r_0 e^{\frac{\ell - \ell_0}{2\ell_0}}$$

$$m(\ell) = m(\ell_0) e^{\left(\frac{\ell}{\ell_0} - 1\right)}$$

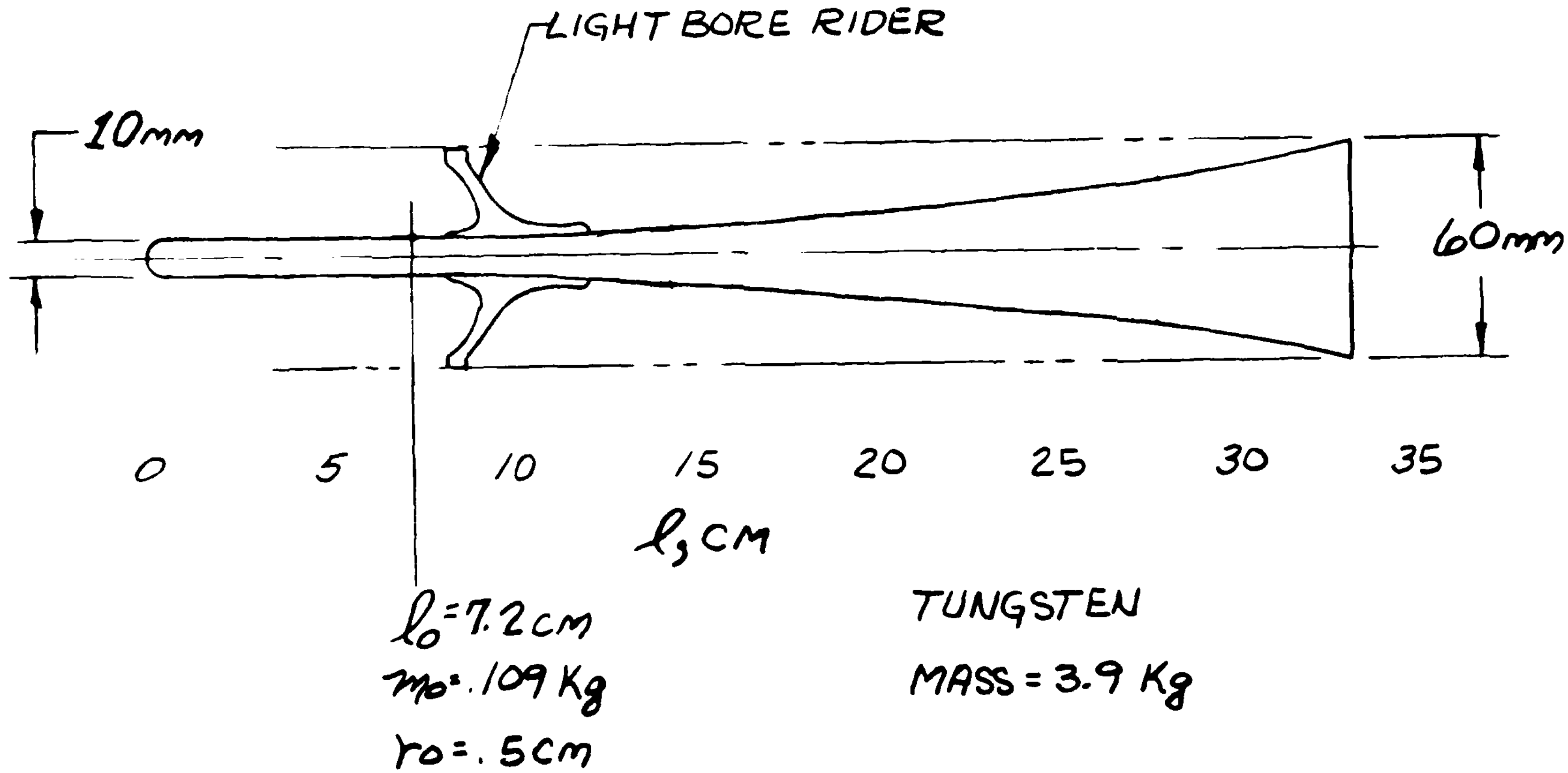

FIGURE 4. PROJECTILE WHOSE TOTAL MASS IS DEFINED AS PENETRATOR

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